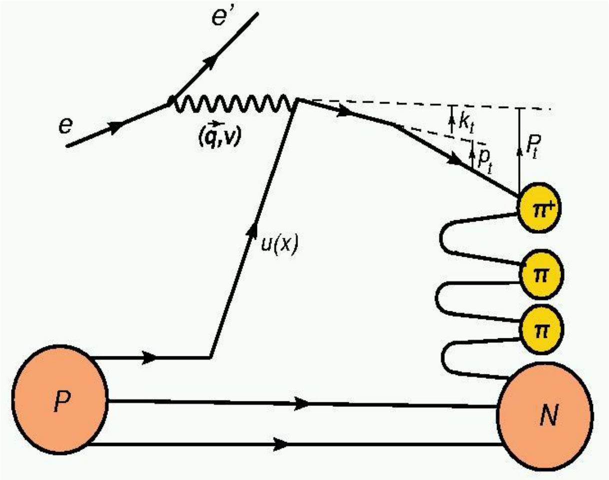
Hall C SIDIS Program – basic (e,e'π) cross sections

Why need for (e,e'π) cross sections?

PAC Report: "the **cross sections** are **such basic tests of the understanding of SIDIS** at 11 GeV kinematics that they will play a **critical role** in establishing the entire SIDIS program of studying the partonic structure of the nucleon. In particular they complement the CLAS12 measurements in areas where the precision of spectrometer experiments is essential, being able to separate P_T and ϕ-dependence for small P_T."



Final transverse momentum of the detected pion **P_T** arises from convolution of the struck quark transverse momentum **k_t** with the transverse momentum generated during the fragmentation **p_t**.

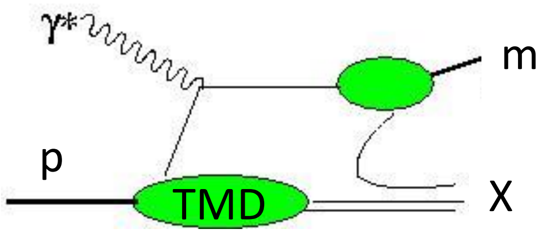
$$P_T = p_t + z\, k_t + O(k_t^2/Q^2)$$

Goal: Map the P_T dependence ($P_T \sim \Lambda < 0.5$ GeV) of π^+, π^- **and π^0** production off proton ~~and deuteron~~ targets to study$^{(*)}$ the k_T dependence of (unpolarized) up and down quarks

(*) Can only be done using spectrometer setup capable of %-type measurements (an essential ingredient of the global SIDIS program!)

Transverse momentum dependence of SIDIS

Linked to framework of Transverse Momentum Dependent Parton Distributions



$TMD^q(x,k_T)$

N \ q	U	L	T
U	f_1		$h_1^\perp$
L		g_1	$h_{1L}^\perp$
T	$f_{1T}^\perp$	g_{1T}	h_1 $h_{1T}^\perp$

Unpolarized target

Longitudinally pol. target

Transversely pol. target

Unpolarized k_T-dependent SIDIS: in framework of Anselmino et al. described in terms of convolution of quark distributions q and (one or more) fragmentation functions D, each with own characteristic (Gaussian) width

→ **Emerging new area of study**

I. Integrated over p_T and ϕ

Hall C: PRL 98:022001 (2007)

Hall B: PRD 80:032004 (2009)

II. P_T and ϕ dependence

Hall B: PRD 80:032004 (2009)

Hall C: PL B665 (2008) 20

Hall C: PRC 85:015202 (2012)

$$\sigma = \sum_q e_q^2 q(x) \otimes D(z)$$

Possibility to constrain k_T dependence of up and down quarks *separately* by combination of π^+ and π^- final states, proton and deuteron targets

Relies on how well we understand SIDIS process → π^0

SIDIS Formalism

General formalism for (e,e'h) coincidence reaction w. polarized beam:

[A. Bacchetta et al., JHEP 0702 (2007) 093]

$$\frac{d\sigma}{dx\,dy\,d\psi\,dz\,d\phi_h\,dP_{h,t}^2} = \frac{\alpha^2}{xyQ^2}\frac{y^2}{2(1-\varepsilon)}\left(1+\frac{\gamma^2}{2x}\right)\Big\{F_{UU,T}+\varepsilon F_{UU,L}+$$

$$\sqrt{2\varepsilon(1+\varepsilon)}\cos\phi_h F_{UU}^{\cos\phi_h}+\varepsilon\cos(2\phi_h)F_{UU}^{\cos(2\phi_h)}+\lambda_e\sqrt{2\varepsilon(1+\varepsilon)}\sin\phi_h F_{LU}^{\sin\phi_h}\Big\}$$

(Ψ = azimuthal angle of e' around the electron beam axis w.r.t. an arbitrary fixed direction)

Use of polarized beams will provide useful azimuthal beam asymmetry measurements (**F_{LU}**) at low p_T complementing CLAS12 data

If beam is unpolarized, and the (e,e'h) measurements are fully integrated over ϕ, only the **$F_{UU,T}$** and **$F_{UU,L}$** responses, or the usual transverse (σ_T) and longitudinal (σ_L) cross section pieces, survive.

Main emphasis proposal: Transverse momentum dependence of SIDIS

$F_{UU}^{\cos(\phi)}$ and $F_{UU}^{\cos(2\phi)}$

(Approved experiment E12-09-017 addresses extensive charged-pion data set)

Hall C SIDIS Program – basic (e,e'π) cross sections

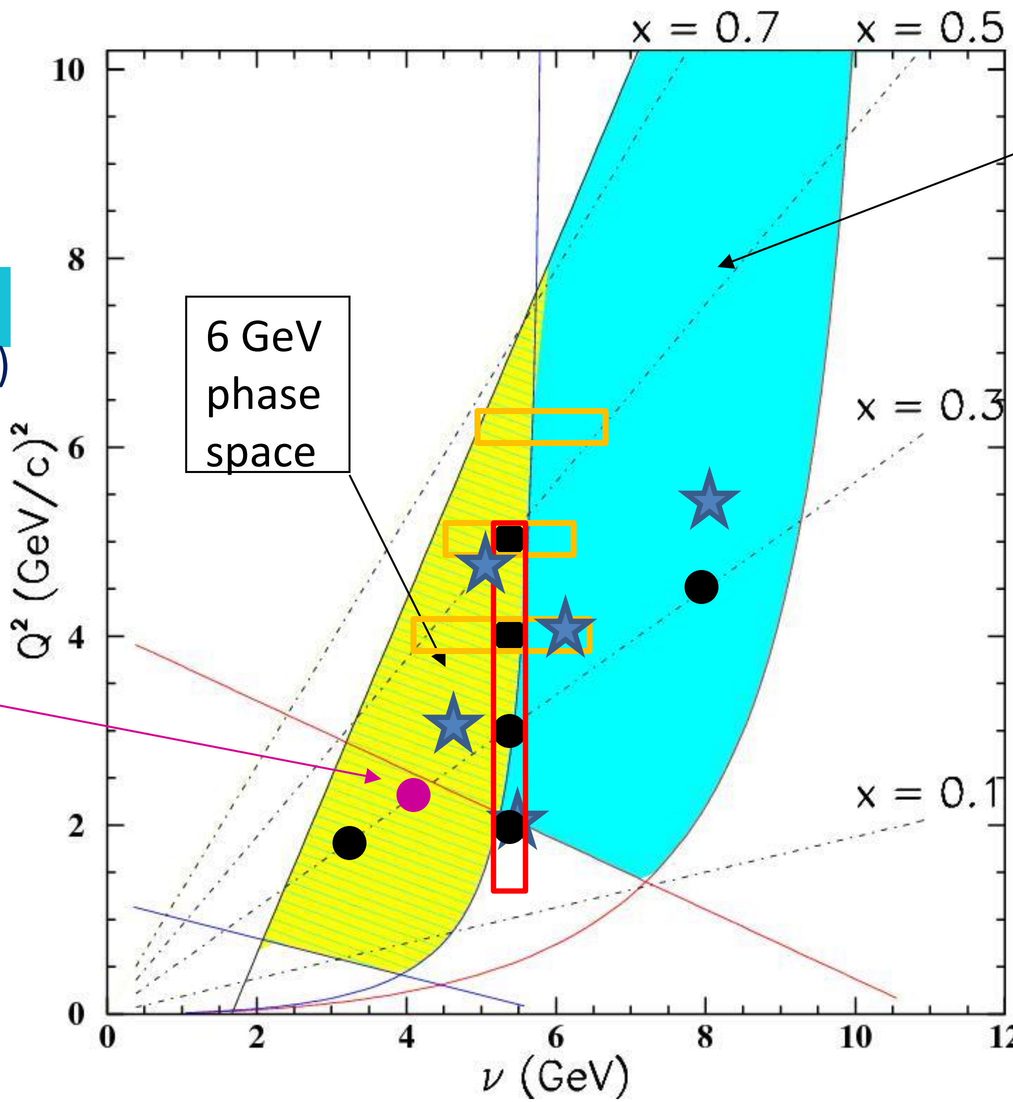
Low-energy (x,z) factorization at JLab-12 GeV must be well validated to substantiate the SIDIS science output

Why need for (e,e'π^0) beyond (e,e'$\pi^{+/-}$)?

- No diffractive ρ contributions
- Smaller radiative tail
  - no pole contributions
- Less resonance region contributions
  - for example, compare with ep → e$\pi^-\Delta^{++}$
- Proportional to average fragmentation function
  - easier to disentangle quark and fragmentation functions

Hall C SIDIS Program Kinematics (typ. x/Q^2 ~ constant)

HMS + SHMS Accessible Phase Space for Deep Exclusive Scattering



π^0 kinematics
Scan in (x,z,p_T)
Overlap with E12-09-017

E00-108

Charged pions:

E12-06-104
L/T scan in (z,p_T)
No scan in Q^2 at fixed x: $R_{DIS}(Q^2)$ known

E12-09-017
Scan in (x,z,p_T)
+ scan in Q^2 at fixed x

E12-09-002
+ scans in z

For semi-inclusive, less Q^2 phase space at fixed x due to:
i) $M_X^2 > 2.5$ GeV^2; and ii) need to measure at both sides of Θ_γ

E12-09-017 Kinematics & possible π^0 Kinematics

Map of P_T dependence in x and z, and in Q^2 to check (p_T/Q) and (p_T^2/Q^2) behavior

Kin	x	Q^2 (GeV^2)	z	Days
I	0.2	2.0	0.3 -0.6	4.5
II	0.3	3.0	0.3 -0.6	5.8
III	0.4	4.0	0.3 -0.6	5.3
IV	0.5	5.0	0.3 -0.6	5.3
V	0.3	1.8	0.3 -0.6	6.9
VI	0.3	4.5	0.3 -0.6	4.0

Each kinematics requires an angle (P_T) scan to cover up to P_T ~ 0.4 (0.5) GeV well (o.k.)

Kin	x	Q^2 (GeV^2)	z	Days
a	0.2	2.0	0.4 -0.8	1
b	0.36	4.0	0.3 -0.8	3
c	0.5	4.8	0.4 -0.8	5
d	0.36	3.0	0.5 -0.8	1
e	0.36	5.5	0.3 -0.8	5

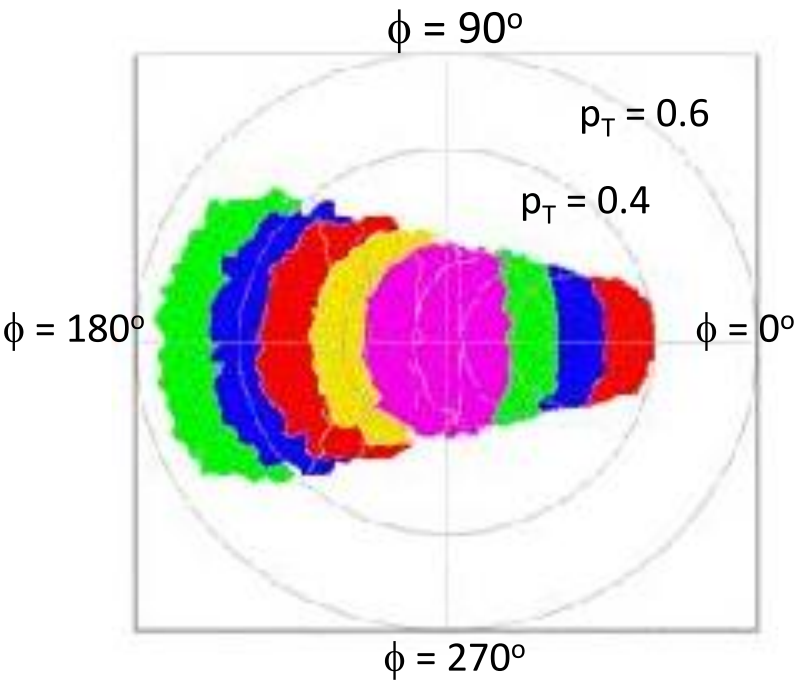
Each kinematics/days identical to DVCS, to cover up to P_T ~ 0.3 (0.4) GeV well (o.k.)

Spin-offs:
- Radiative correction modeling for (e,e'π)
- Single-spin asymmetries at low p_T (< 0.2 GeV)

E12-09-017: P_T coverage

Can do meaningful measurements at low p_T (down to 0.05 GeV) due to excellent momentum and angle resolutions!

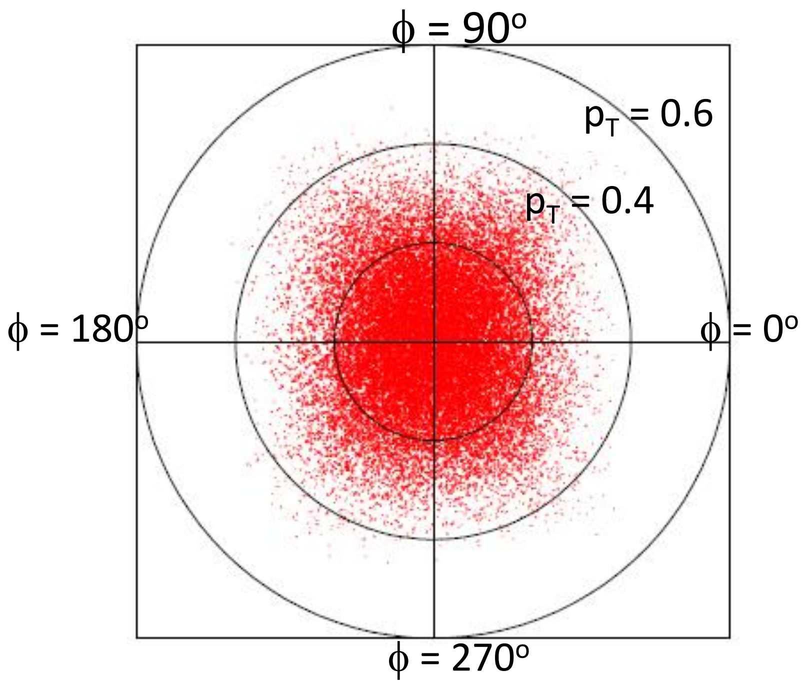
- Excellent ϕ coverage up to p_T = 0.2 GeV
- Sufficient up to p_T = 0.4 GeV
  → coverage at $\phi = 0, \pi$
- Limited up to p_T = 0.5 GeV
  → use f(ϕ) from CLAS12



SIDIS π^0: P_T coverage

Basic SIDIS cross sections with excellent precision, and very good momentum and angle resolutions!

- Excellent ϕ coverage up to p_T = 0.2 GeV
- Sufficient up to p_T = 0.3 GeV
- Limited up to p_T = 0.4 GeV
  → use f(ϕ) from CLAS12

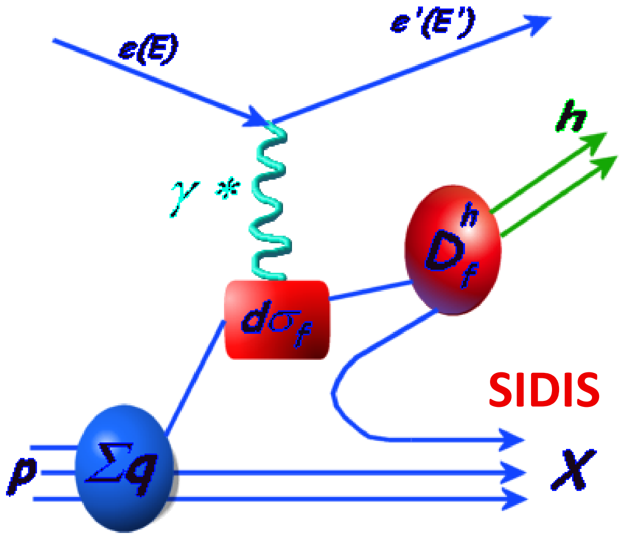


π^0 SIDIS count rate estimate at z = 0.6

Kin	x	Q^2 (GeV^2)	Days	Counts (1 μA)
a	0.2	2.0	1	150K
b	0.36	4.0	3	60K
c	0.5	4.8	5	30K
d	0.36	3.0	1	40K
e	0.36	5.5	5	30K

Seems very reasonable, even for 1 μA

SIDIS – Flavor Decomposition



DIS probes only the sum of quarks and anti-quarks → requires assumptions on the role of sea quarks

$$\sum e_q^2(q+\bar{q})$$

Solution: Detect a final state hadron in addition to scattered electron

→ Can 'tag' the flavor of the struck quark by measuring the hadrons produced: 'flavor tagging'

$z = E_\pi/\nu$

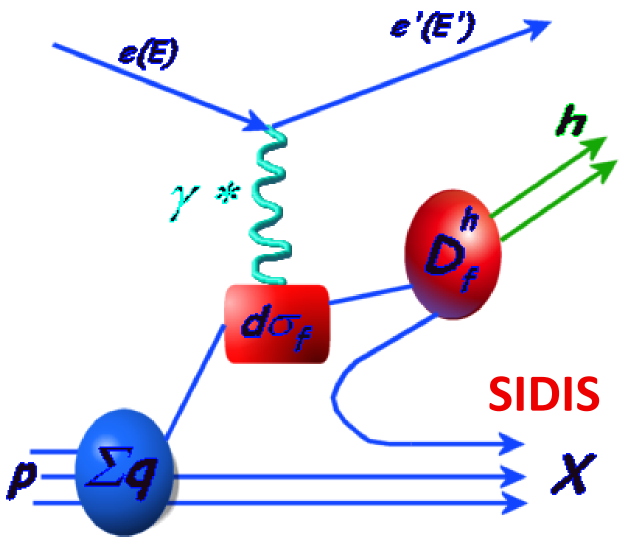
$$\frac{1}{\sigma_{(e,e')}}\frac{d\sigma}{dz}(ep \to hX) = \frac{\sum_q e_q^2 f_q(x) D_q^h(z)}{\sum_q e_q^2(x) f_q(x)}$$

$f_q(x)$: parton distribution function

$D_q^h(z)$ fragmentation function

- Leading-Order (LO) QCD
- after integration over p_T and ϕ
- NLO: gluon radiation mixes x and z dependences

SIDIS – Flavor Decomposition



(M,0)

DIS probes only the sum of quarks and anti-quarks → requires assumptions on the role of sea quarks

$$\sum e_q^2(q+\bar{q})$$

Solution: Detect a final state hadron in addition to scattered electron

→ Can 'tag' the flavor of the struck quark by measuring the hadrons produced: 'flavor tagging'

(e,e') $M_x^2 = W^2 = M^2 + Q^2\,(1/x - 1)$

(For M_m small, $\vec{p}_m$ collinear with $\vec{\gamma}$, and $Q^2/\nu^2 << 1$)

(e,e'm) $M_x^2 = W'^2 = M^2 + Q^2\,(1/x - 1)(1 - z)$

$M_x^2 = W'^2$ ⇄ z

$z = E_m/\nu$

How Can We Verify Factorization?

Neglect sea quarks and assume no p_t dependence to parton distribution functions

→ Fragmentation function dependence drops out in Leading Order

$$\rightarrow [\sigma_p(\pi^+) + \sigma_p(\pi^-)]/[\sigma_d(\pi^+) + \sigma_d(\pi^-)]$$

$$= [4u(x) + d(x)]/[5(u(x) + d(x))]$$

$$\sim \sigma_p/\sigma_d$$

independent of z and p_t

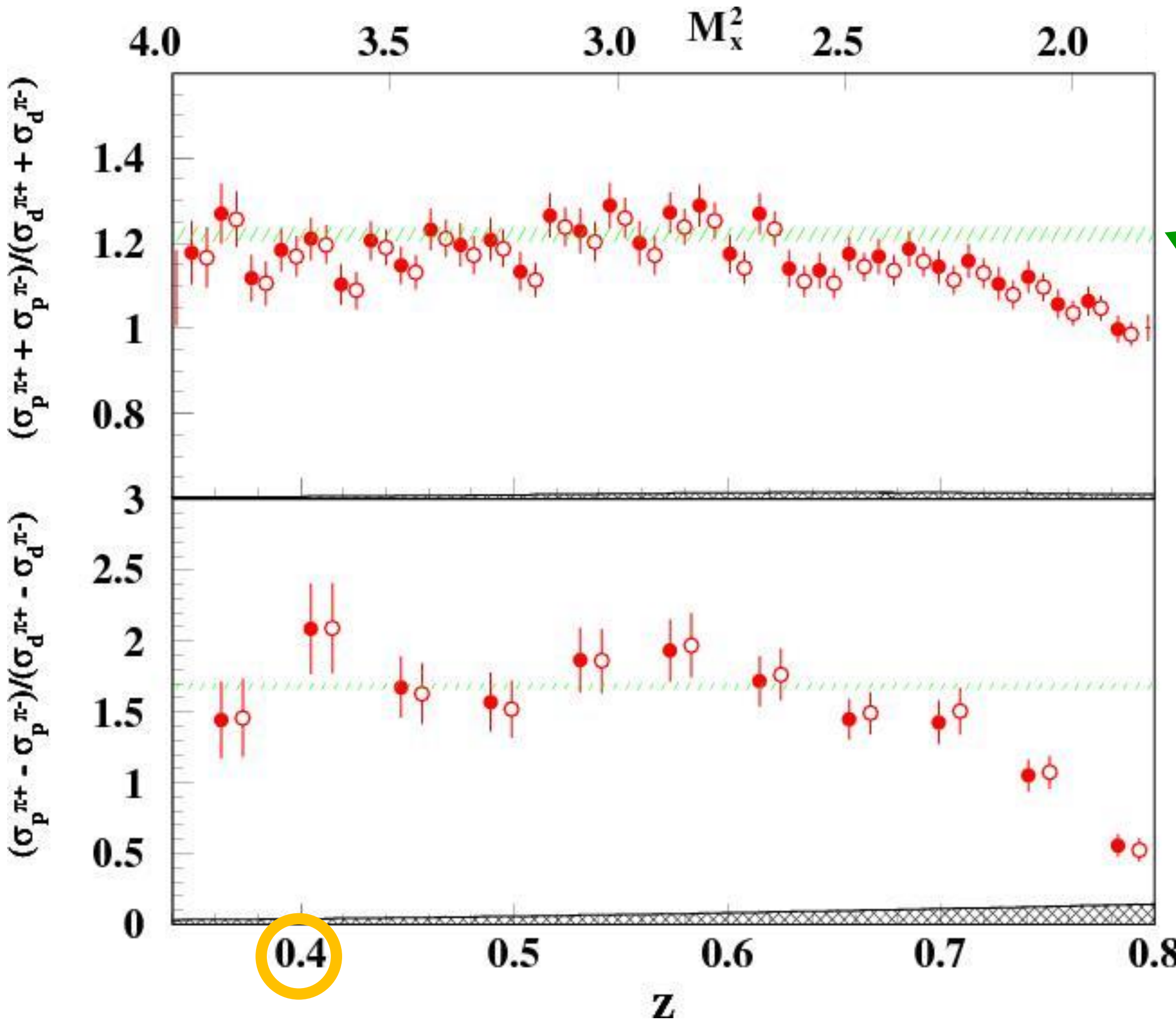
$$\rightarrow [\sigma_p(\pi^+) - \sigma_p(\pi^-)]/[\sigma_d(\pi^+) - \sigma_d(\pi^-)]$$

$$= [4u(x) - d(x)]/[3(u(x) + d(x))]$$

independent of z and p_t,

but more sensitive to assumptions

E00-108: Onset of the Parton Model



GRV & CTEQ, @ LO or NLO

Good description for p and d targets for 0.4 < z < 0.65

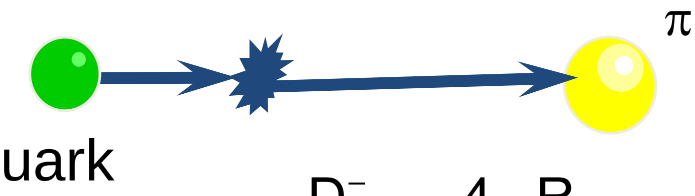
(Note: z = 0.65 ~ M_x^2 = 2.5 GeV^2)

Closed (open) symbols reflect data after (before) events from coherent ρ production are subtracted

E00-108: Onset of the Parton Model

$$\Sigma e_q^{\,2} q(x)\, D_q^{\pi}(z)$$

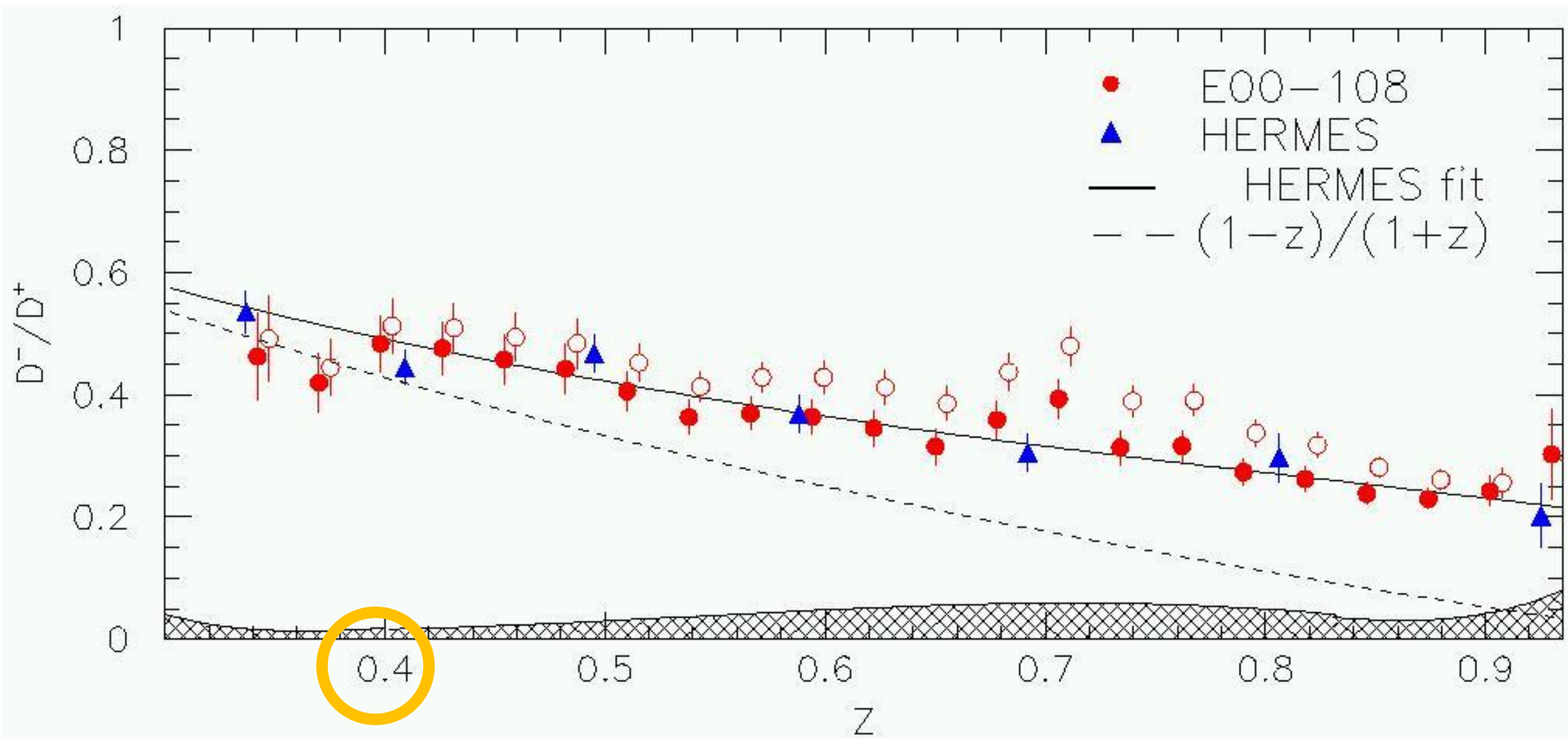
factorization



Collinear Fragmentation

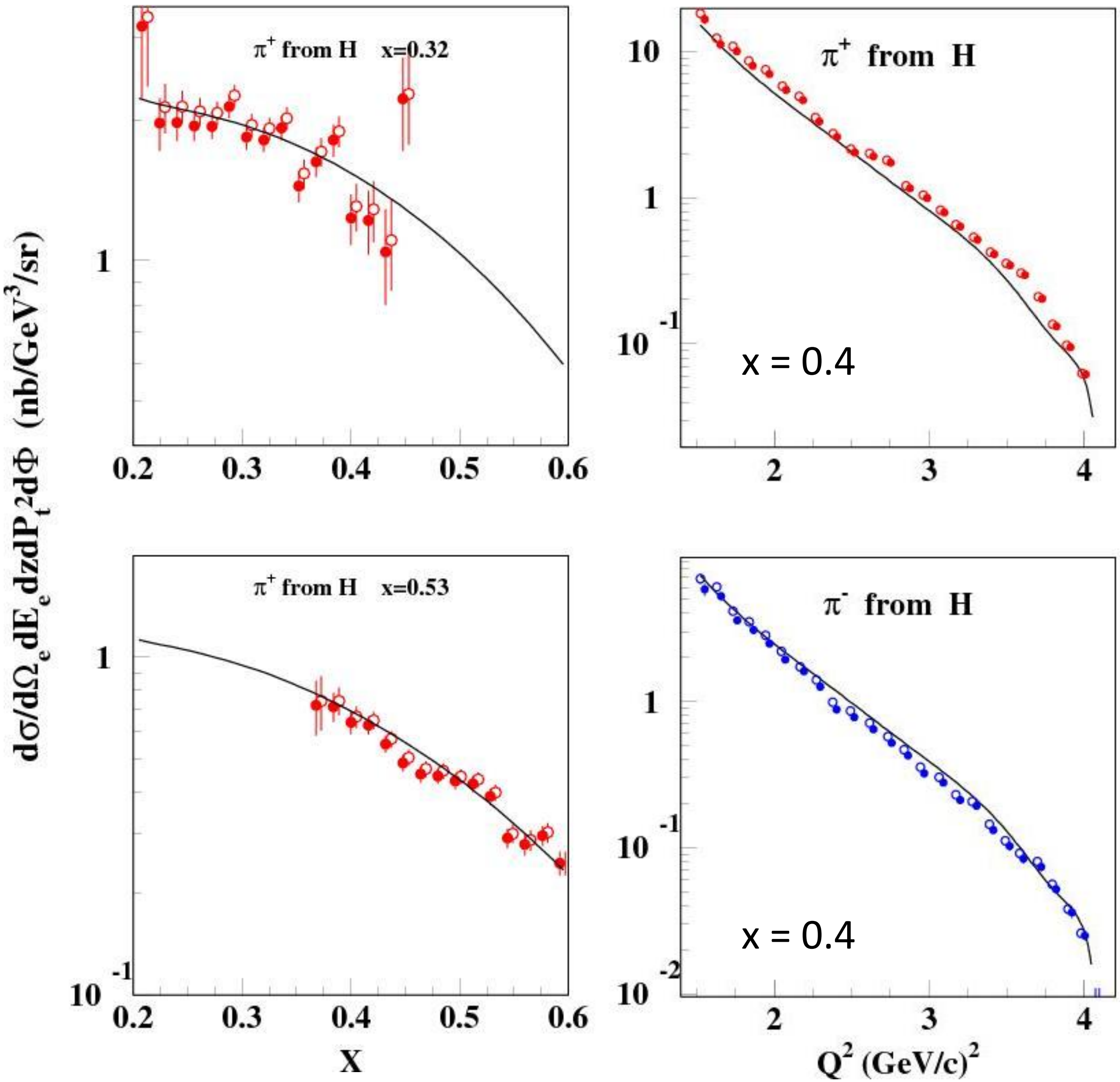
$$\frac{D^-}{D^+} = \frac{4-R}{4*R-1} \qquad R = \frac{N_{\pi^+}}{N_{\pi^-}}$$

(Deuterium data)



(Resonances cancel (in SU(6)) in D^-/D^+ ratio extracted from deuterium data)

E00-108: Onset of the Parton Model

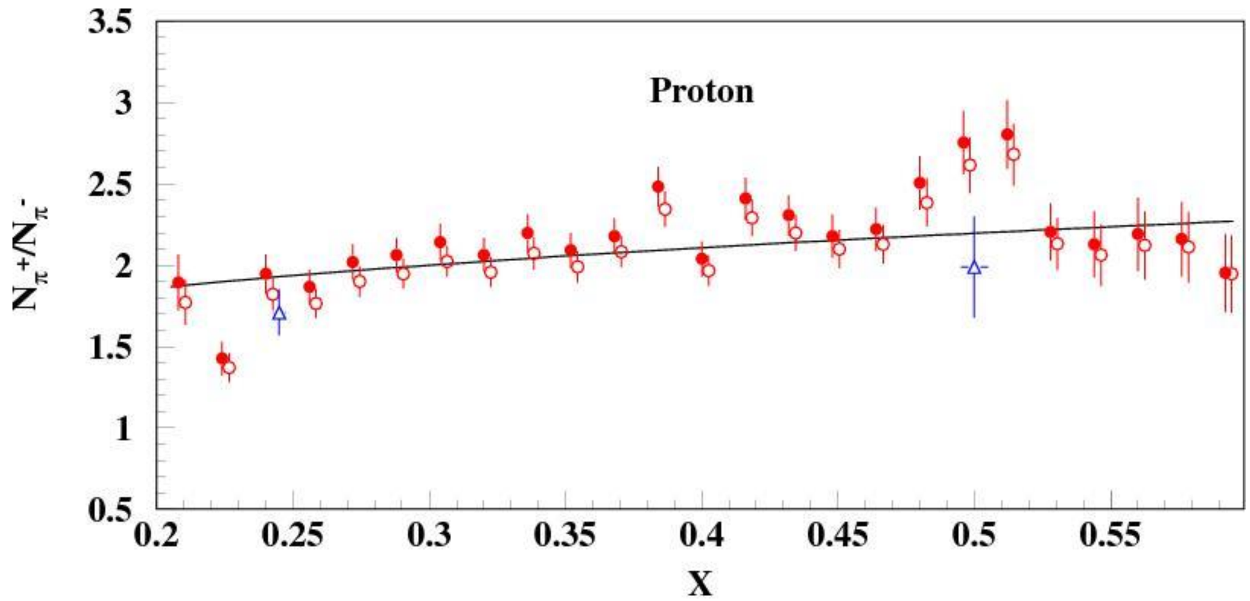


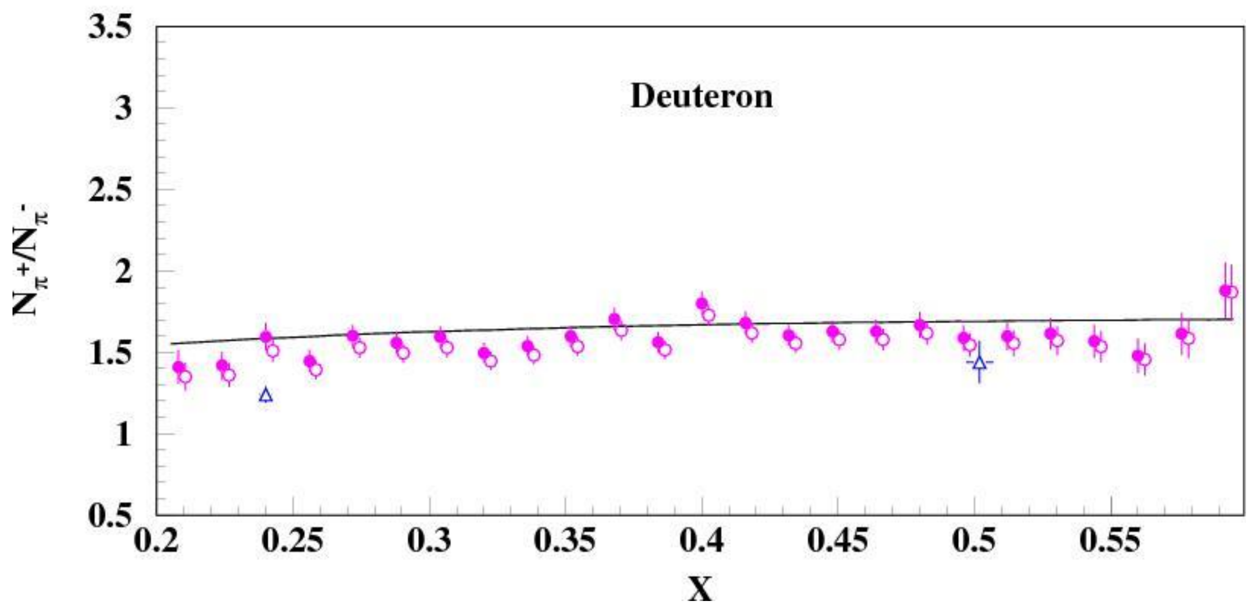
Solid (open) symbols are after (before) subtraction of diffractive ρ events

Solid curve is a naïve parton model calculation assuming CTEQ5M parton distribution functions at NLO and BKK fragmentation functions

Overall, one finds good agreement, but there are detailed differences in the cross section measurements (also for the deuterium target)

E00-108: Onset of the Parton Model





Solid (open) symbols are after (before) subtraction of diffractive ρ events. Blue symbols are old Cornell measurements.

Solid curve is a naïve parton model calculation assuming CTEQ5M parton distribution functions at NLO and BKK fragmentation functions

Agreement with the naïve parton model expectation is always far better for ratios, also for D/H, Al/D, or ratios versus z or Q^2.